BNL Contributions to the Main Injector Neutrino Oscillation Search

DOE Science and Technology Review, May 20 2010

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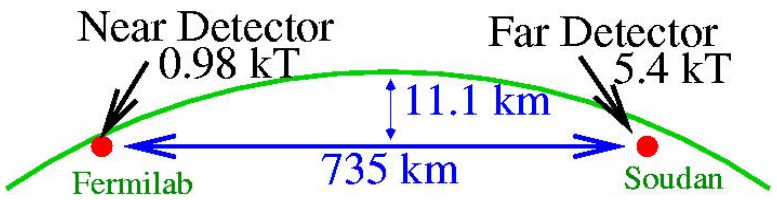
Brookhaven National Laboratory

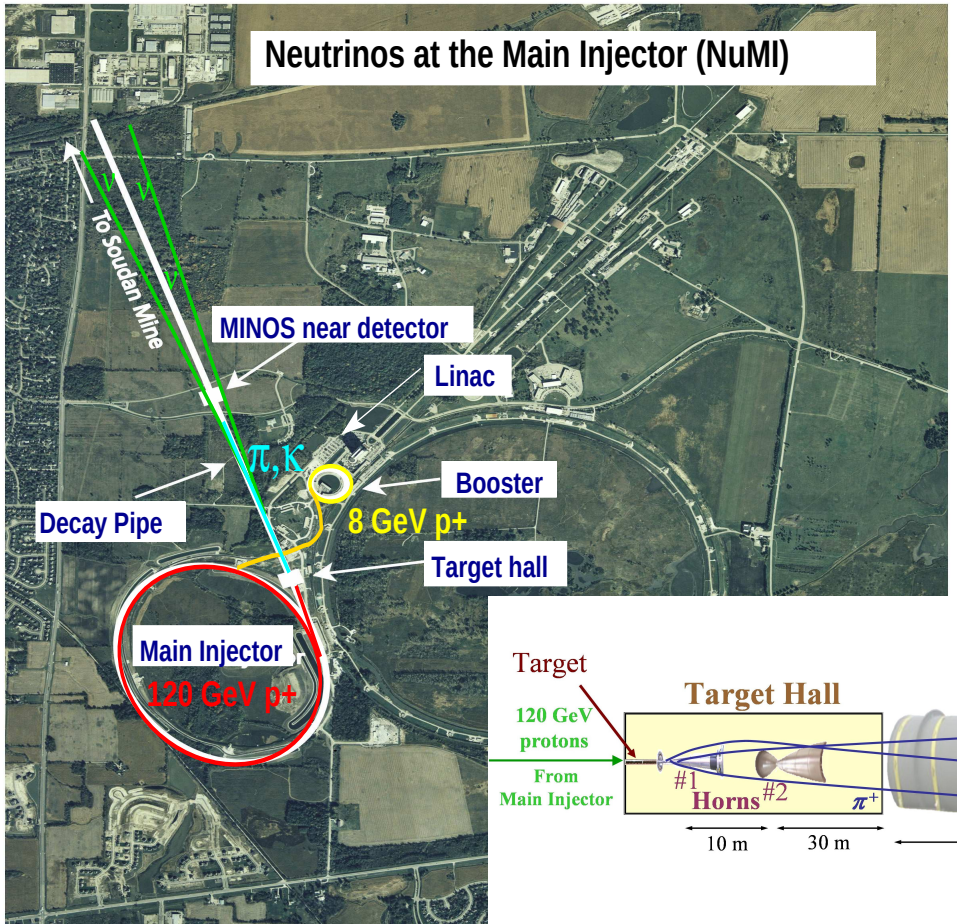
May 19, 2010

The NuMI/MINOS Accelerator ν_μ Experiment

Observe $\nu_\mu/\bar{\nu}_\mu$ disappearance, ν_e appereance, atmospheric $\nu/\bar{\nu}$ oscillations, search for ν_s

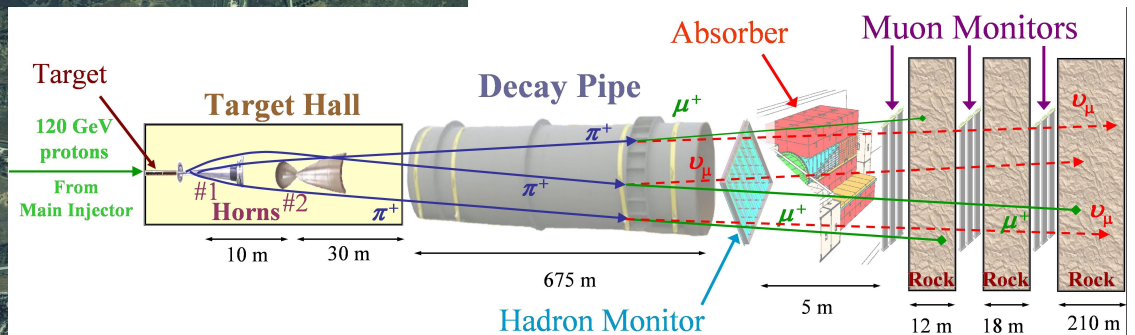


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**



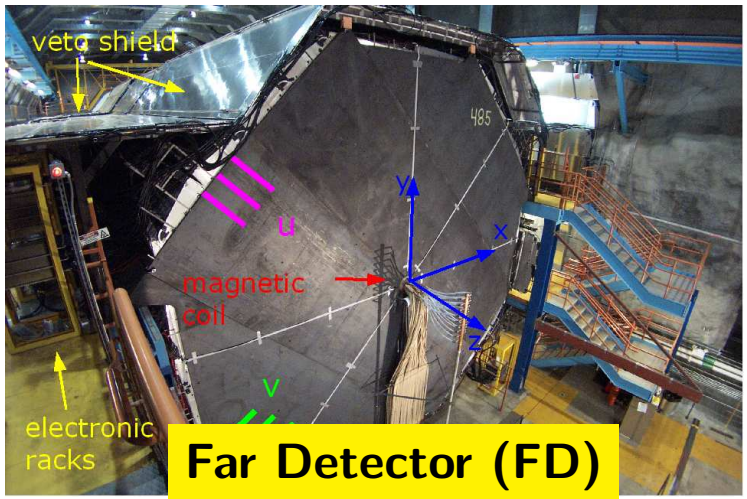
NuMI Horn 2 inner conductor
Radial field, B $\propto$ 1/r

3T at 200 kA



The MINOS Detectors

Magnetized iron calorimeters with 2.54 cm thick Fe plates sandwiched with scintillator strips readout by WLS fiber.



Far Detector (FD)

Near Detector (ND)

- **484 octogonal steel and scintillator plates 8m wide, $\Rightarrow$ 5.4kTon and 30 m in length.**
- **Toroidal B-field, 1.3 T at r = 2m**
- **Cosmic μ veto shield**

- **282 "squashed" octagonal steel plates, 153 scintillator planes. $\Rightarrow$ 1kTon and 16 m in length.**
- **Toroidal B-field, 1.3 T at r = 2m**

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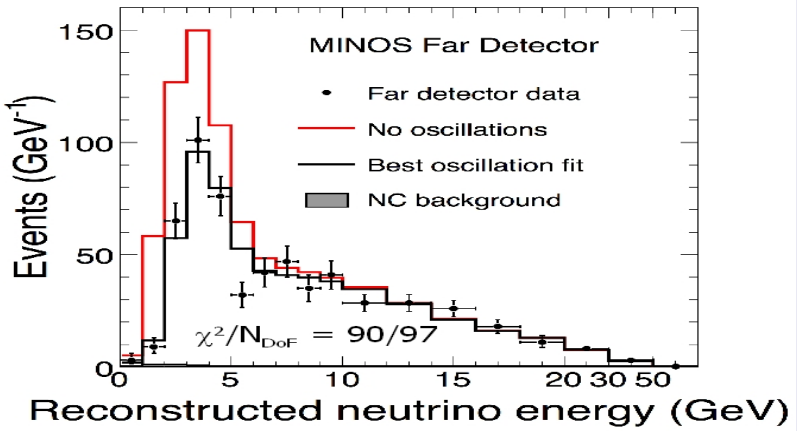
MINOS Results - 2009 (3.5×10^{20} protons-on-target)

The NuMI beam contains 91.5% ν_μ, 7 % $\bar{\nu}_\mu$ and 1.5% $\nu_e + \bar{\nu}_e$

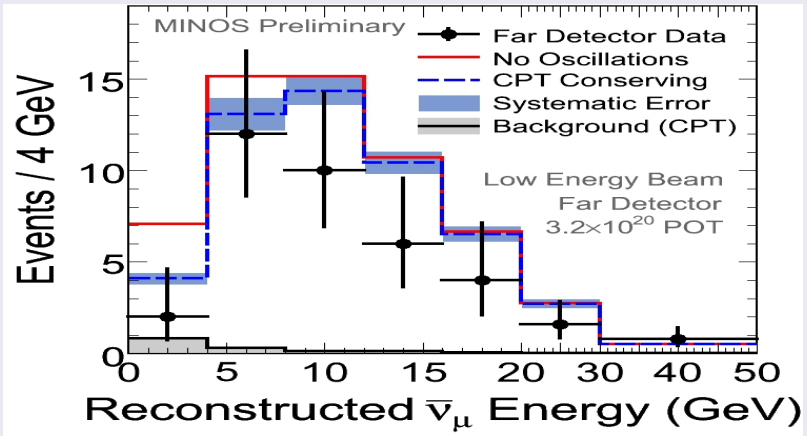
ν_μ disappearance

PRL 101, 2008



Expected no-osc 1065 $\pm$ 60.
Observe 848.

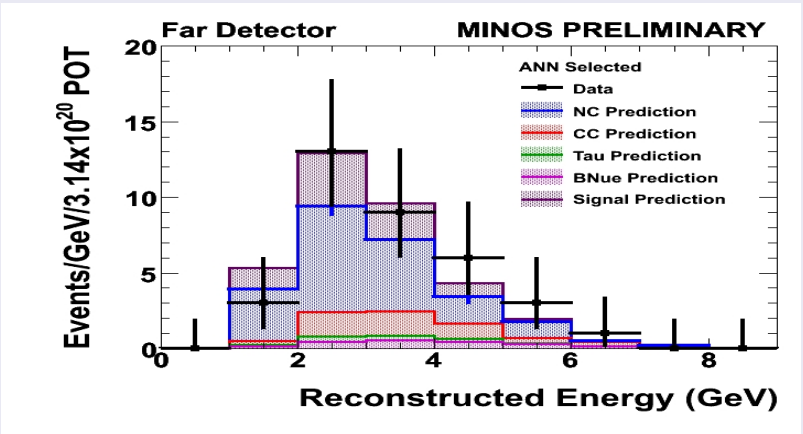
$\bar{\nu}_\mu$ disappearance



Expected (with osc) 58.3 $\pm$ 7.6$_{stat}$ $\pm$ 3.6$_{sys}$.
Observe 42.

ν_e appearance

PRL 103, 2009



Expected FD background: 27 $\pm$ 5$_{stat}$ $\pm$ 2$_{sys}$.
Observe 35.

MINOS results 2009:

ν_μ Disappearance:

$\Delta m^2_{32} = 2.43 \pm 0.13 \times 10^{-3} eV^2$ **world best**

$\sin^2 2\theta_{23} > 0.90 (90\% C.L.)$

$\bar{\nu}_\mu$ Disappearance:

Fraction $\nu_\mu \rightarrow \bar{\nu}_\mu < 0.026 (90\% C.L.)$

ν_e appearance:

$\sin^2 2\theta_{13} < 0.29 (90\% C.L.); \Delta m^2 > 0, \delta_{cp} = 0$

$\sin^2 2\theta_{13} < 0.42 (90\% C.L.); \Delta m^2 < 0, \delta_{cp} = 0$

Search for ν_s

BROOKHAVEN NATIONAL LABORATORY

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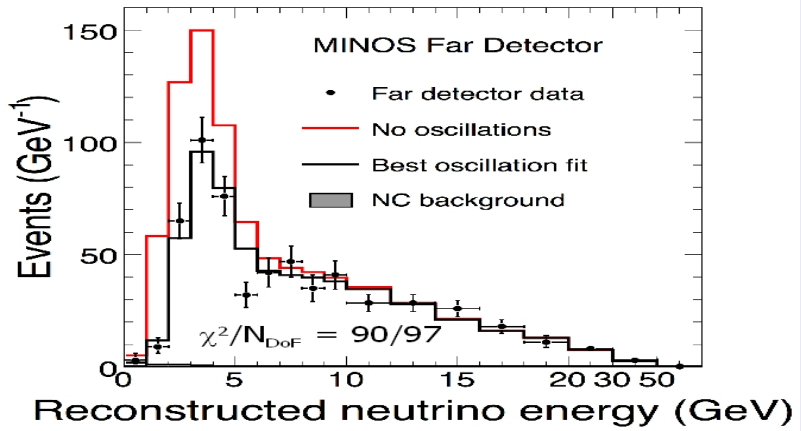
PRL 101, 2008



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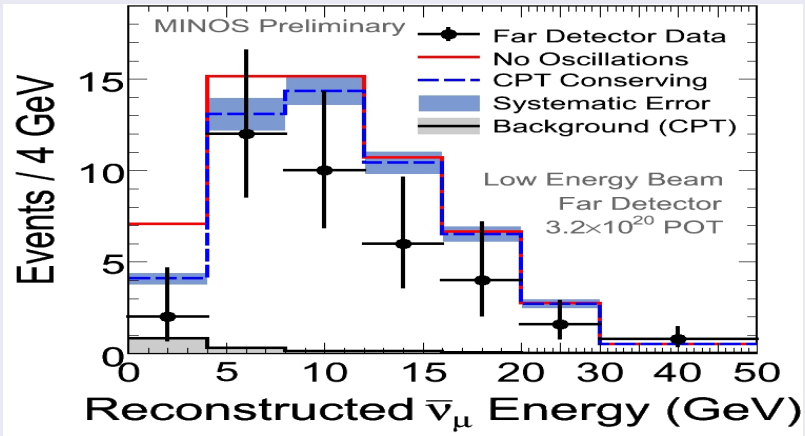
$\bar{\nu}_\mu$ disappearance



Expected (with osc) 58.3 $\pm$ 7.6$_{stat}$ $\pm$ 3.6$_{sys}$.
Observe 42.

ν_e appearance 2010

7×10^{20} protons-on-target Expect 3σ sensitivity at $\sin^2 2\theta_{13} = 15\%$
Lisa Whitehead, BNL Colloquium 4/9/2010 Getting ready for publication

MINOS results 2009:

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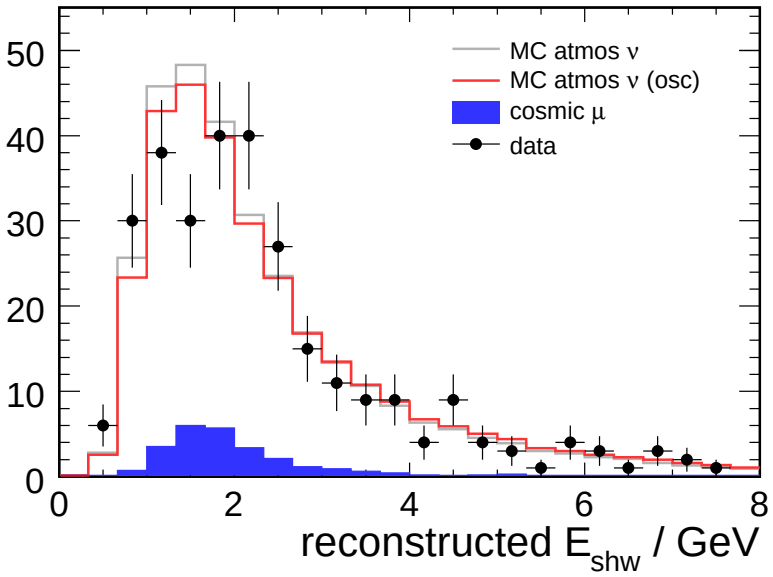
Search for ν_s

BNL People and Activities 2009-2010

Person	Position	MINOS activities
Mary Bishai	Physicist	Beam systematics co-convener. Finalized NuMI beam flux systematics for 2010 oscillation analysis.
Milind Diwan	Physicist	Former ν_e analysis co-convener. 2009 $\bar{\nu}_\mu$ oscillation analysis internal reviewer.
David Jaffe	Physicist	$\bar{\nu}_\mu$ oscillation analysis. 2009 ν_e appearance analysis internal reviewer (PRL 103, 2009).
Brett Viren	Physicist	Beam data software maintenance and beam simulations.
Lisa Whitehead	Research Associate	ν_e analysis co-convener (April 2010). ν_e analysis backgrounds, sensitivity. 2010 ν_μ analysis internal reviewer.
Kevin Zhang	Research Associate (now at NYIT)	Atmospheric ν_e analysis.

Atmospheric ν_e Results 24.6 kT-Yrs

Kevin Zhang and David Jaffe (BNL) lead the effort to measure the atmospheric ν_e event rate in the FD. *These events are used to normalize the total atmospheric neutrino flux in the FD for the atmospheric ν_μ oscillation analysis.*



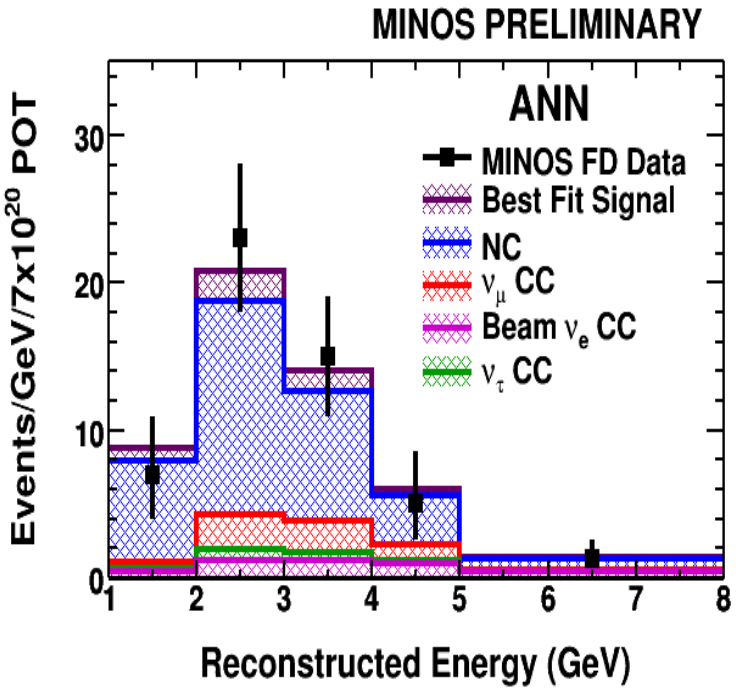
PRD draft of MINOS atmospheric analysis, including completed atmospheric ν_e analysis, currently being reviewed by collaboration.

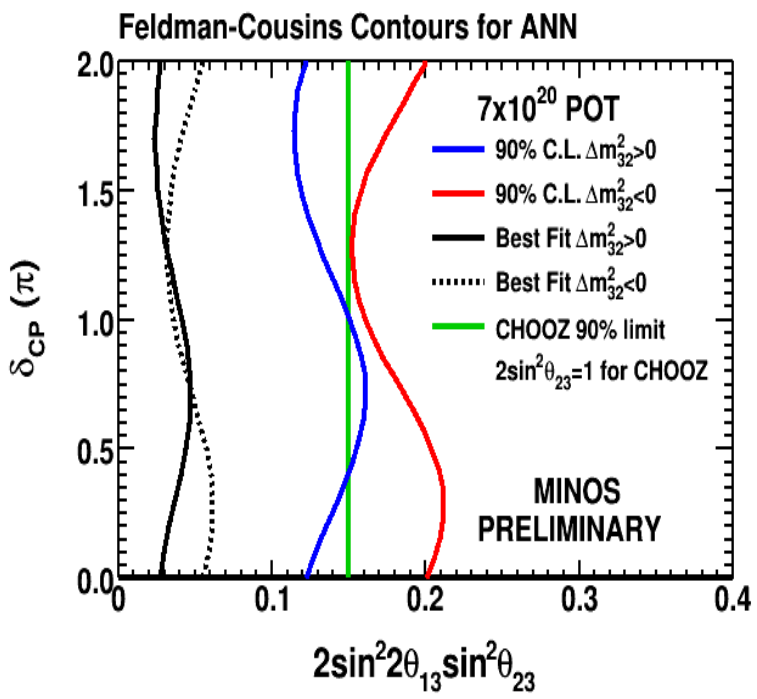
Data	Expectation ($\Delta m^2_{32} = 2.5 \times 10^{-3}\text{eV}^2, \sin^2 2\theta_{23} = 1.0$)				
	cosmic μ	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ CC	$\nu_\tau/\bar{\nu}_\tau$ CC	NC
292	26 ± 3	47 ± 7	159 ± 24	12 ± 2	57 ± 14
292	301 ± 43				

New MINOS Results: Search for $\nu_\mu \longrightarrow \nu_e$ Oscillations 2010

Observe 54 events

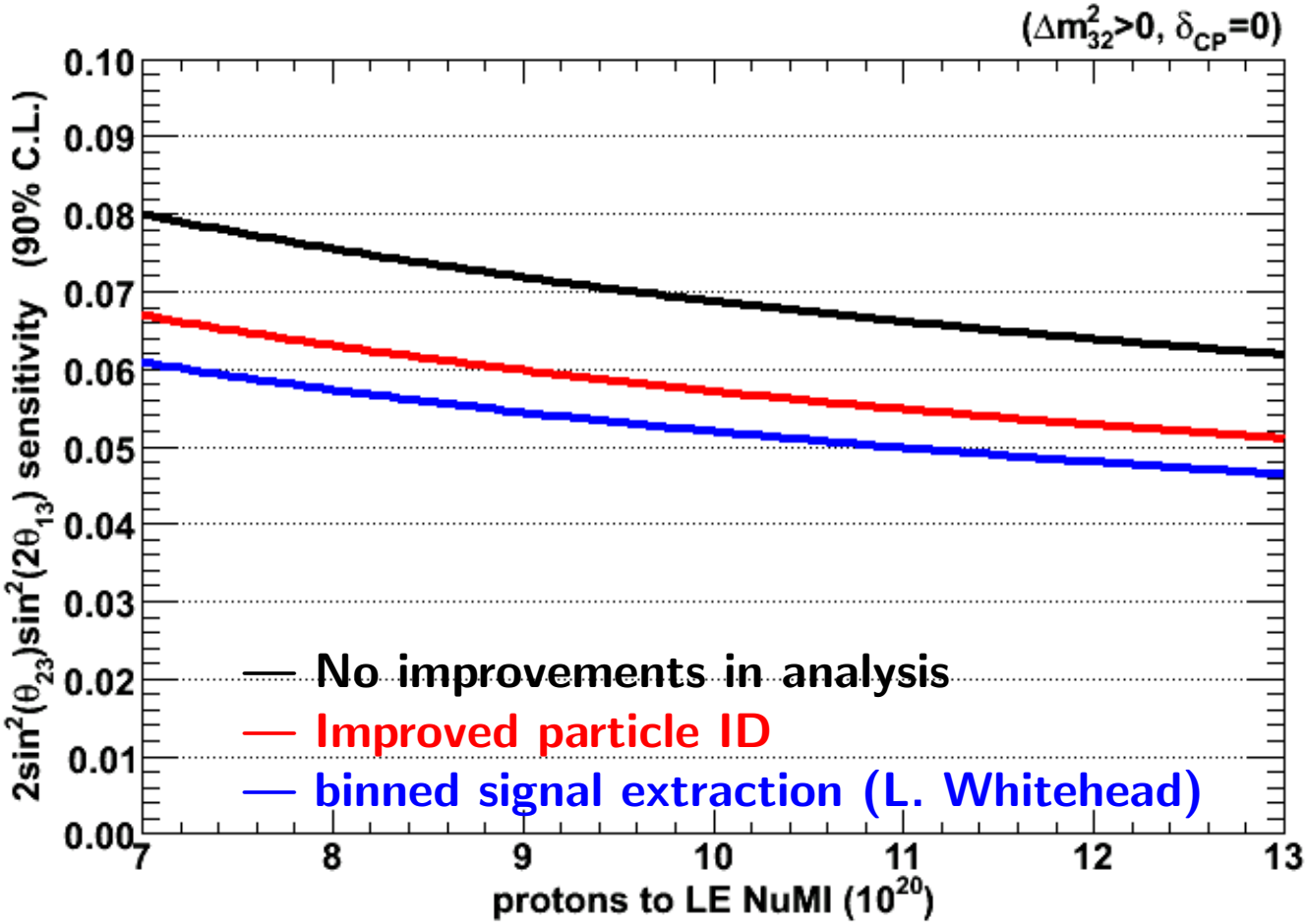
Expected Background 49.1 $\pm$ 7.0(stat) $\pm$ 2.7(syst)





Lisa Whitehead (BNL) responsible for FD background predictions, systematic uncertainties and sensitivity calculations.PRL in preparation

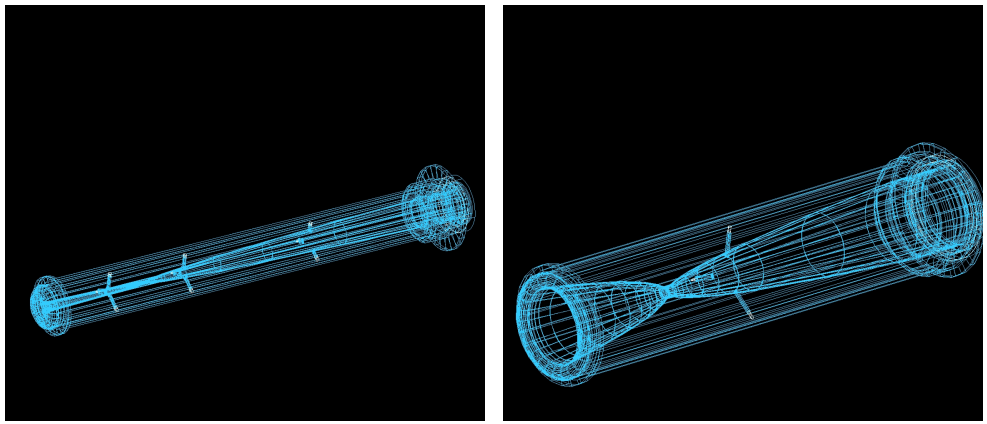
Future Plans for MINOS ν_e Analysis with 13×10^{20} protons to NuMI by 2011



Double Chooz single detector sensitivity:
$\sin^2 2\theta_{13} < 0.06$ at 90% C.L. (2012 ?)

Lisa Whitehead (BNL) appointed ν_e analysis co-convener in April 2010

MINOS Beam Systematics Group Efforts '09-'10
M. Bishai co-convener



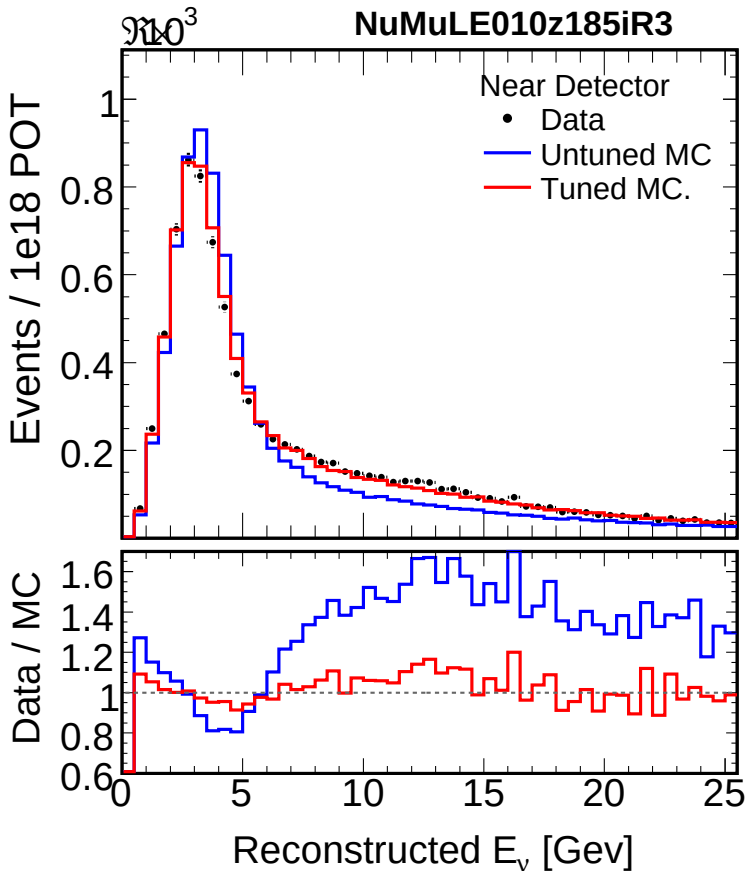
- **Implementation and validation of a detailed NuMI beam-line simulation using the FLUKA08 hadro-production model and GEANT4 geometry. This was necessary to improve the modeling of production in the decay pipe after He was added in 2007 (GEANT3 model did not match near detector data).**
- **Re-evaluation of hadro-production and geometry systematics with He in the decay pipe and accurate beam-line material for ALL '09-'10 MINOS/NuMI analysis results.**
- **Understanding MINOS target degradation**

M. Bishai heavily involved in determining oscillation systematics due to beam modeling uncertainties.

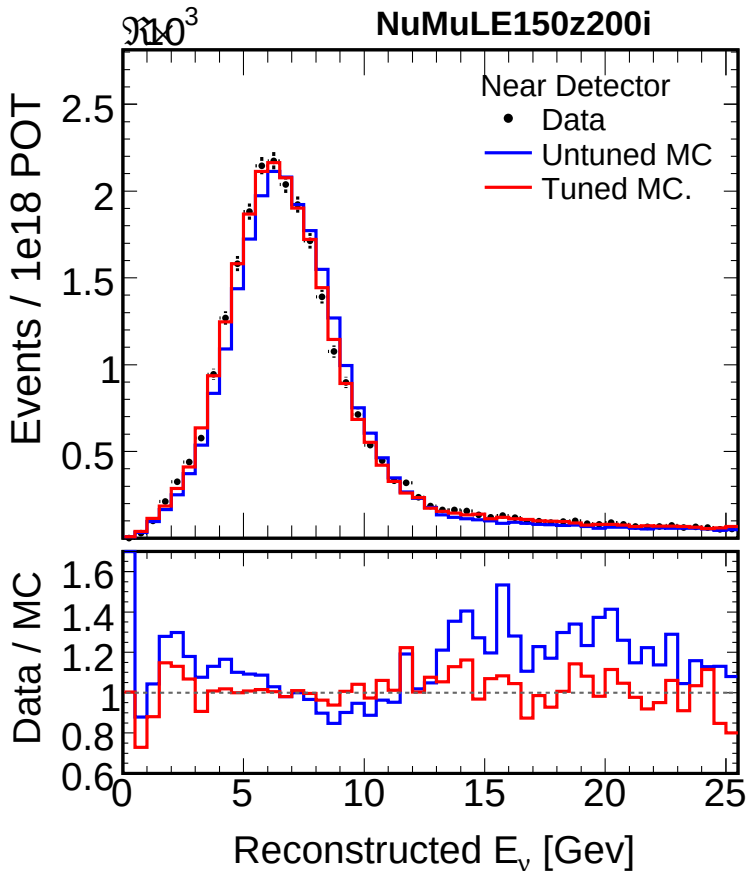
Beam fits to MINOS ND Data, 2010

A multi-parameter fit of the MINOS MC to the observed ND event rate was optimized to separate detector effects from beam effects. The fit is performed simultaneously to $\nu_\mu, \bar{\nu}_\mu$ in different NuMI beam configurations.

NuMI low-energy beam tune

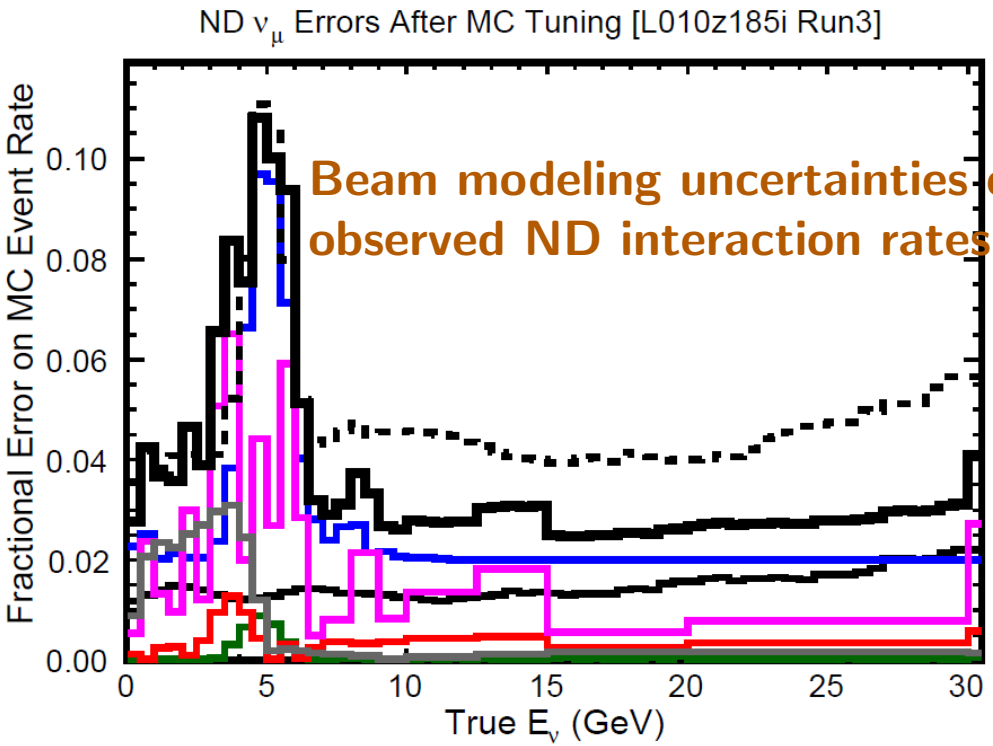


NuMI medium-energy beam tune



NuMI Beam Modeling Uncertainties

- - - Previous fit
— Target decay model
— Horn material budget
— New this fit
— Hadron production
— Target damage
— Beam optics
— Target position



Beam related uncertainties on ND event rate $\leq$ 11%

focusing/target damage uncertainties dominate.

Publication in preparation.

NuMI Beam Modeling Uncertainties

- - - Previous fit
— Target decay model
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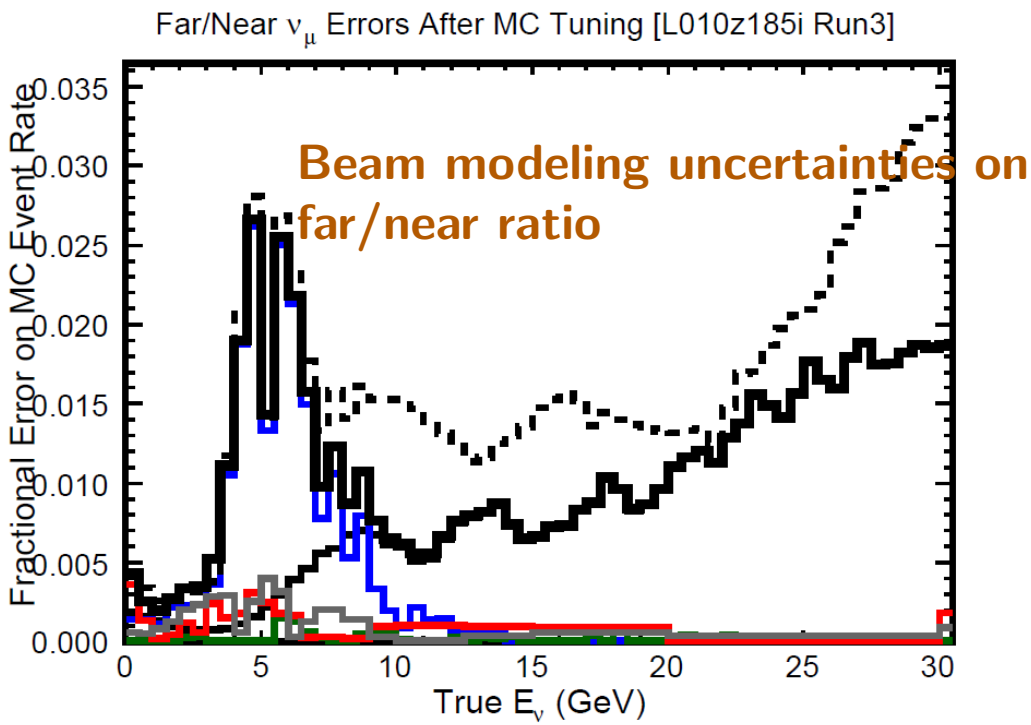
— Target position



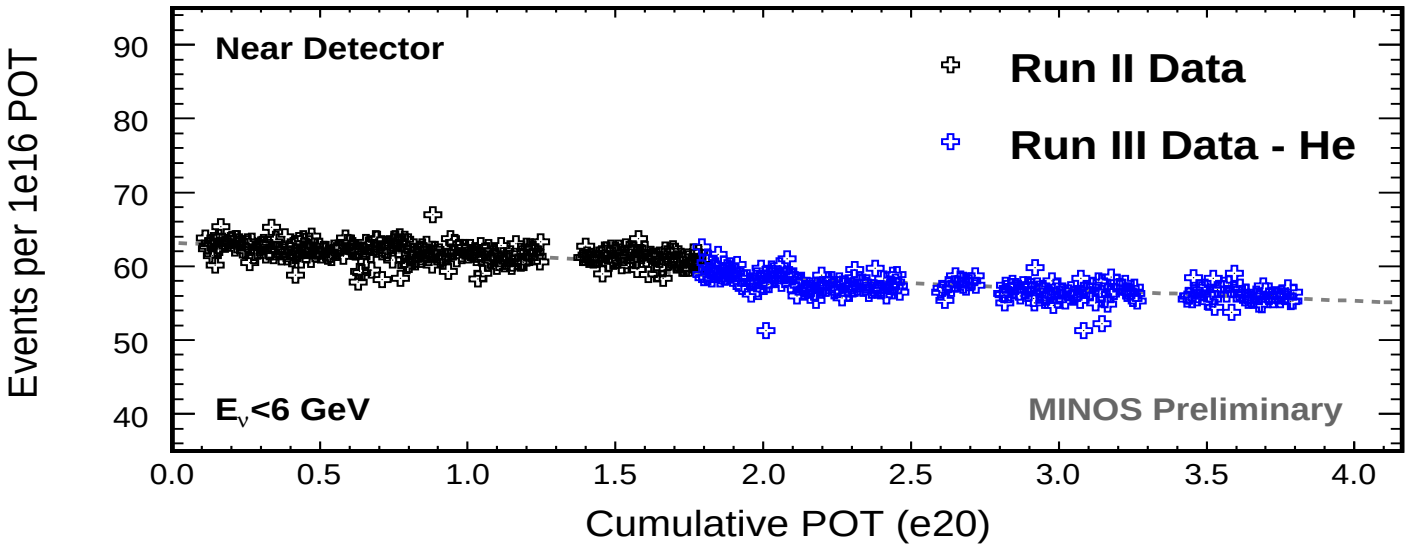
Beam related uncertainties on ND to FD event rate extrapolation is $< 3\%$

focusing/hadro-production uncertainties dominate.

Publication in preparation.

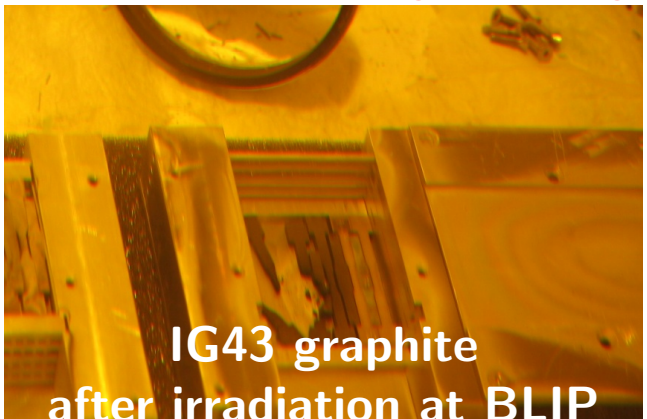
Proton Target Radiation Damage

BNL is responsible for the normalization of the MINOS beam event rates to protons-on-target



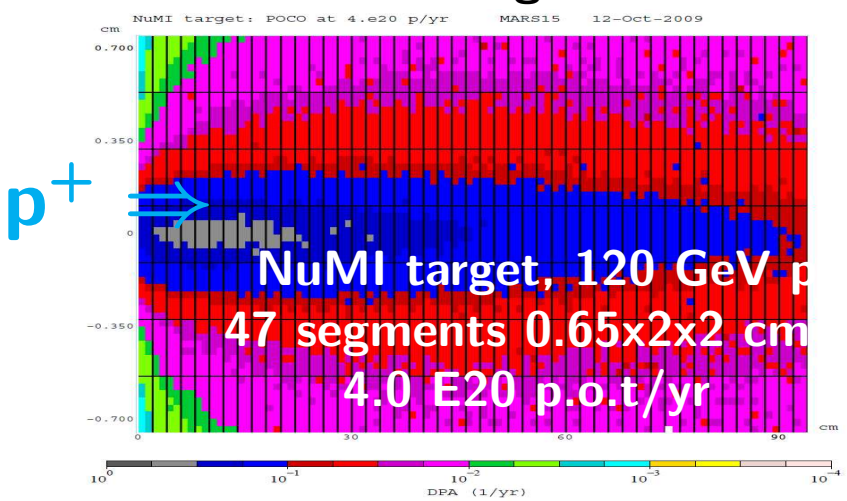
Mary Bishai and David Jaffe (BNL) demonstrated that the observed drop in the ND normalized low energy ν rate is consistent with target damage.

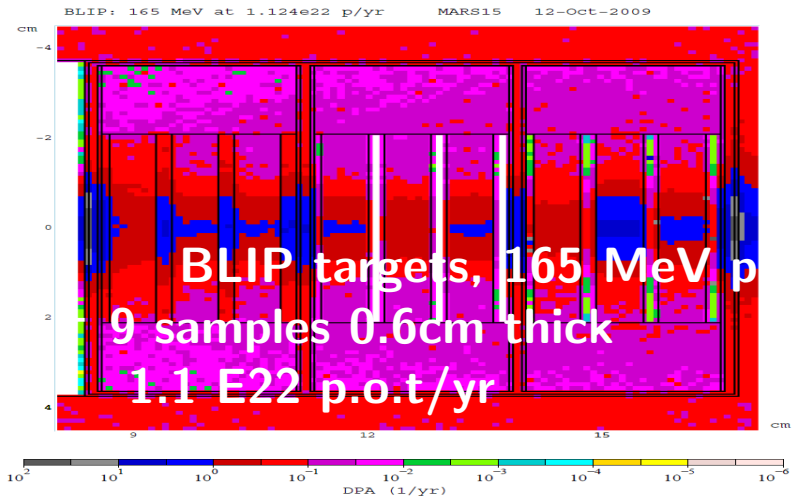
Independent studies **by Nick Simos (BNL-EST) of p^+ beam irradiation damage using 165 MeV protons at the BNL BLIP facility provide critical input for modeling rad. damage effects in the NuMI target.**



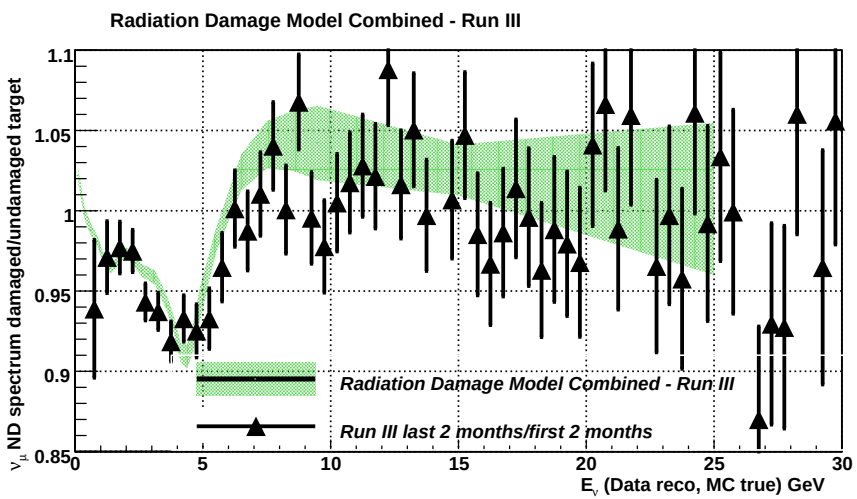
Proton Target Radiation Damage

Nikolai Mokhov (FNAL) simulated the energy deposition in both the NuMI and BLIP targets:





Proton radiation damage in 4 weeks at BLIP ≡ 0.4 MW yr at NuMI



Mary Bishai implemented a model of the target damage into the NuMI simulation.

⇐ Model fits the observed change in MINOS ND spectrum. validates BLIP extrapolation to NuMI AND LBNE!

Summary

- **The BNL MINOS group has been involved in a wide variety of successful MINOS analysis efforts: $\bar{\nu}_\mu$ oscillation, $\nu_\mu \rightarrow \nu_e$ appearance search, measurement of the atmospheric ν_e flux in the FD, beam modeling systematics.**
- **The BNL MINOS group in collaboration with other local experts and utilizing unique BNL facilities are providing critical information for understanding MINOS beam data.**
- **BNL group members continue to serve as analysis group co-conveners and lead several analysis efforts in 2010.**
- **We continue to be responsible for online beam monitoring and beam data quality and proton counting.**
- **The BNL MINOS group's expertise on NuMI/MINOS analysis and beam simulations has been critical in producing the first LBNE beam designs and making the physics case.**

MINOS publications 2009/2010

- **"Search for sterile neutrino mixing in the MINOS long baseline experiment". MINOS collaboration, Phys. Rev. D 81, 052004 (2010).**
- **"Neutrino and Antineutrino inclusive Charged Current Cross Section Measurements with the MINOS Near Detector". MINOS collaboration, Phys. Rev. D 81, 072002 (2010).**
- **"Observation of muon intensity variations by season with the MINOS far detector". MINOS collaboration, Phys. Rev. D 81, 012001 (2010).**
- **"Search for muon-neutrino to electron-neutrino transitions in MINOS". MINOS collaboration, Phys. Rev. Let. 103, 261802 (2009).**
- **"Sudden stratospheric warmings seen in MINOS deep underground muon data". MINOS collaboration, Geophys. Res. Lett. 36, L05809 (2009).**